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Investigations of nonlinear dynamic performance of top-and-seat with web angle connections subjected to sudden column removal

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ABSTRACT

It is well known that progressive collapse is a complicated dynamic process with geometry and material nonlinearities. Sudden column removal scenario is a simple yet effective method for analysis and design of structures to mitigate progressive collapse. The main objective of this study is to investigate the dynamic performance of top-and-seat with web angle (TSWA) steel beam–column connections under progressive collapse condition. This type of connection represents typical bolted cleat connections with excellent ductility. Each specimen consisted of two adjoining beams pinned at the far ends and connected to a middle column stub. Five dynamic tests for the TSWA connections subjected to sudden removal of the middle columns were conducted in Nanyang Technological University. Another five corresponding static tests were also carried out for comparison with the dynamic behaviour. Test results showed that the release-time durations of the column support force were around 30 ms for all the five dynamic tests. Transient dynamic responses with free vibrations were observed for the connections following instantaneous removal of the middle columns. The maximum dynamic displacement was significantly increased compared to the static connection response. In addition, numerical simulations were also conducted using the general-purpose finite element software ABAQUS. The three-dimensional finite element model was validated by comparing the simulation results against the test data. Parametric studies were carried out to investigate the full dynamic connection performance and its structural resistance under push-down analysis to simulate progressive collapse. By comparing the full dynamic response with its corresponding quasi-static response, both the displacement-based dynamic increase factor (DIF) and force-based DIF were investigated, respectively. The paper ends with some discussions on practical applications of displacement-based DIF and force-based DIF.

1. Introduction

Progressive collapse failure of a building may result in very serious economic consequences, casualties and property losses. With an increase of terrorist attack activities against civilian structures, there are greater research efforts world-wide to mitigate progressive collapse. Alternate load path approach is one of the major design methods in GSA 2003 [1] and DoD 2010 [2] guidelines to ensure that structural systems have adequate resistance to progressive collapse. It is a threat-independent approach which requires a structure to redistribute the imbalance loads after the loss of a primary load-bearing member. This design approach is generally applied in the context of a "missing-column" scenario to assess the structural potential to progressive collapse.

One of the key issues in progressive collapse is that it is a complicated dynamic and nonlinear phenomenon. Currently, a wide range of numerical analyses have been conducted for investigating the responses of various structural buildings to progressive collapse. In most of these studies, due to extensive time and resources required for fully nonlinear dynamic analyses, engineers assume sudden column removal scenarios to analyse structures based on non-linear static analysis incorporating dynamic increase load factors (DIF). Clearly, there is an urgent need to investigate if such an approach can accurately represent the dynamic response of a structure. In this regard, Kaewkulchai and Williamson [3] proposed a beam element formulation and solution procedure to study the dynamic response of plane frames during progressive collapse. Analysis results highlighted the significance of dynamic load redistribution for progressive collapse. In the research work conducted by Khandelwal and El-Tawil [4], a computational macro-model has been developed for nonlinear dynamic progressive collapse analyses of steel structures. The local and global responses have been

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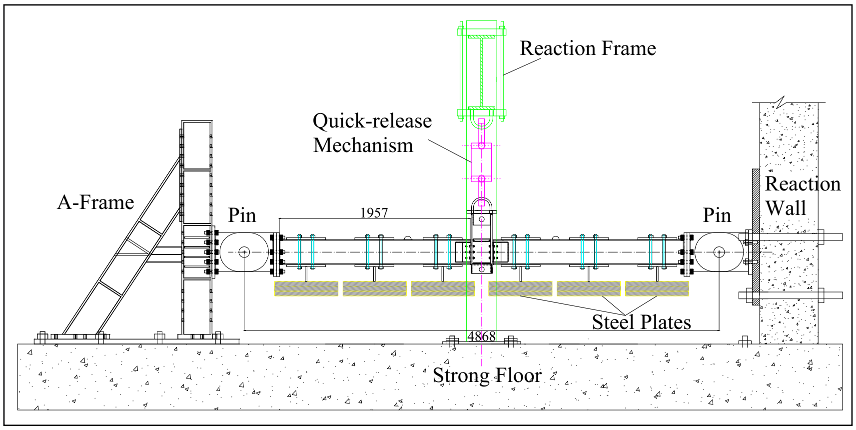

Fig. 1. Dynamic test setup.

captured by incorporating the component-based joint behaviour (i.e. joint failure, panel zone deformation, etc.) into the numerical models. Recently, a more complicated three-dimensional finite element model was proposed by Fu [5,6] to investigate the dynamic behaviour of a 20-strorey composite building subjected to the sudden removal of column. Although sudden column removal scenario ignores the effects of blast or impact, it is a simple method for progressive collapse analysis and can be easily applied in design practice. The pertinent question is whether the approach is conservative.

Although there are some reported numerical models for simulating progressive collapse, currently, experimental investigations on dynamic progressive collapse performance of structures undergoing large deformation are still scarce. Karns et al. [7] evaluated the resistance of different types of steel frame connections, initially subjected to blast loads and then being pushed downwards using monotonic static loading method. Experimental and analytical studies have also been carried out by Sasani et al. [8,9] to assess the dynamic response of reinforced concrete structures following instantaneous removal of one or two columns. According to the test results, Vierendeel action was found to be the main load redistribution mechanism. However, due to the absence of live loads in the RC building, structural deformations still remained within the linear elastic region after sudden removal of the columns. This in turn affects the applicability of these test observations for a better understanding of structural behaviour associated with large deformations and material nonlinearities. For example, if there are sufficient horizontal restraints from surrounding undamaged structural members, catenary action in beams may be mobilised to resist progressive collapse. Therefore, there is still an urgent need and demand for experimental work to gain a deeper insight into the dynamic performance of structures to progressive collapse.

From 2009 to 2012, a research programme has been conducted in Nanyang Technological University Singapore to investigate the dynamic behaviour of steel beam–column connections subjected to sudden column removal scenarios. Several experimental studies [10,11] showed that beam–column connections are the primary components to maintain robustness and to mitigate progressive collapse when extreme loads occur. Recently, Yang and Tan [12] carried out a series of tests to investigate the resistance and ductility of seven types of commonly used steel beam–column connections under catenary action. The connection response was studied by progressively increasing a point load at the middle column until failure occurs. The experimental results demonstrated that catenary action can greatly improve the connection resistance to progressive collapse. Both bolted angle and flush end plate connections are among the best in mobilising catenary action due to their large rotation capacities. As a parallel companion to this series of studies under static loading condition,, the dynamic test

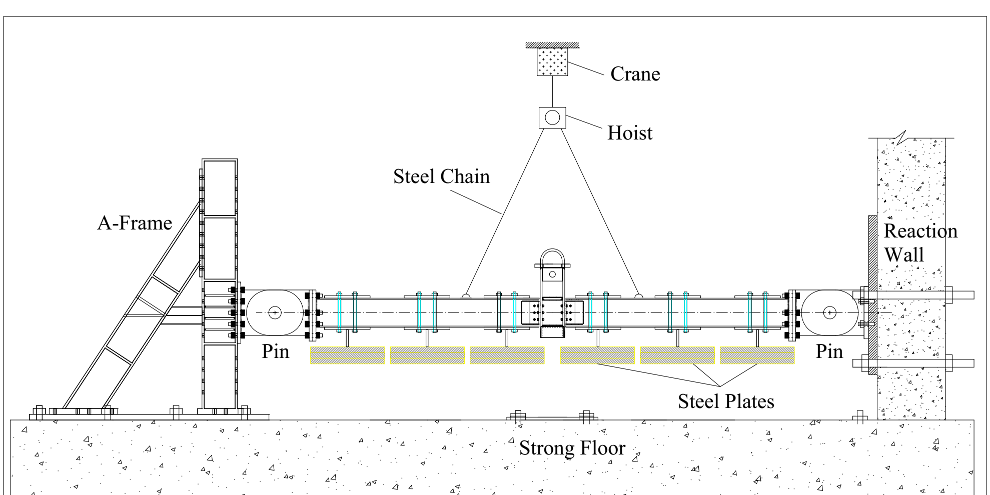

Fig. 2. Static test setup.